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FEASIBILITY TO MEASURE THE PROPERTIES OF IDENTIFIED CHARGED HADRONS IN COLLISIONS OF XENON NUCLEI WITH A FIXED TUNGSTEN TARGET AT AN ENERGY OF 2.5*A* GEV IN THE MPD DETECTOR AT THE NICA COLLIDER

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Abstract. We report results on a feasibility study of measuring the properties of identified charged light hadrons ($\pi^{\pm}$ and $K^{\pm}$ mesons as well as protons) in collisions of Xe nuclei with a fixed tungsten target at an energy of 2.5*A* GeV using the MPD detector at the NICA collider. The evaluations of the purity of the reconstructed spectrum in the MPD detector, reconstruction efficiency of the spectra in the MPD detector and the transverse momentum spectra for the $\pi^{\pm}$, $K^{\pm}$ mesons and protons were made. The evaluations were obtained depending on the transverse momentum for different intervals of centrality of Xe + W collisions in the central rapidity range using model calculations. We used an approach based on σ-parameterization of particle identification information in the MPD detector.

Keywords: nuclei collision, production, hadron, NICA collider, MPD detector

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ВОЗМОЖНОСТИ ИЗМЕРЯТЬ СВОЙСТВА ИДЕНТИФИЦИРОВАННЫХ ЗАРЯЖЕННЫХ АДРОНОВ В СТОЛКНОВЕНИЯХ ЯДЕР КСЕНОНА С НЕПОДВИЖНОЙ ВОЛЬФРАМОВОЙ МИШЕНЬЮ ПРИ ЭНЕРГИИ 2,5*A* ГЭВ В ДЕТЕКТОРЕ MPD НА УСКОРИТЕЛЕ NICA

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Аннотация. В работе исследованы возможности измерять свойства идентифицированных заряженных легких адронов ($\pi^{\pm}$- и $K^{\pm}$-мезонов, а также протонов) в столкновениях ядер ксенона Xe с неподвижной мишенью из вольфрама W при кинетической энергии налетающего пучка E_{kin} = 2,5*A* ГэВ с помощью экспериментальной установки (ЭУ) MPD на ускорителе NICA. Получены оценки чистоты восстанавливаемого спектра в ЭУ MPD, эффективности восстановления спектров в ЭУ MPD и дифференциальных спектров по поперечному импульсу для исследуемых легких адронов. Оценки вычислены как зависимости от поперечного импульса для различных интервалов по центральности столкновений Xe + W в центральной области быстрот посредством модельных расчетов. Использовался подход на основе σ-параметризации информации об идентификации частиц в ЭУ MPD.

Ключевые слова: столкновение ядер, рождение, адрон, ускоритель NICA, детектор MPD

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Introduction

Study of the processes occurring in collisions of relativistic heavy ions and the production of nuclear matter in such collisions is one of the most important areas in high-energy physics [1, 2]. Experiments to study nuclear matter under extreme conditions of high baryon density and/or temperature have been conducted for almost 40 years at various accelerator facilities around the globe. The most significant discovery in this field was the detection of strongly interacting quark-gluon plasma (QGP), behaving as an ideal fluid, at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL, USA) and at the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN, Switzerland) in heavy-ion collisions at center-of-mass energy $\sqrt{S_{NN}}$ = 0.1–5 TeV per nucleon pair [3, 4]. A more detailed analysis of the experimental data accumulated earlier at the Super Proton Synchrotron (SPS) at CERN also confirmed the production of QGP in collisions between heavy nuclei at $\sqrt{S_{NN}}$ approximately equal to 17 GeV [5].

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The results obtained indicate the existence of a transition from hadronic matter to QGP at a critical temperature of approximately 170 MeV and almost zero net-baryon density; such a transition was predicted theoretically by several models [3, 4]. A Beam Energy Scan (BES-I and BES-II) program for nucleus-nucleus collision events was launched at RHIC to construct a phase diagram of the state of strongly interacting nuclear matter in the regions of low temperatures and high net-baryon densities ($\sqrt{S_{NN}}$ = 2–15 GeV), as well as to search for the theoretically predicted critical end point (CEP) of the phase transition [6]. To date, experiments have been unable to uncover CEP. More detailed investigations of the phase diagram in this region are planned for the near future at the Facility for Antiproton and Ion Research (FAIR) at the GSI Helmholtz Centre for Heavy Ion Research (Darmstadt, Germany) [7], at the High Intensity Heavy Ion Accelerator Facility (HIAF) at the Institute of Modern Physics (Huizhou, China) [8], and at the Nuclotron-based Ion Collider fAcility (NICA) at the Joint Institute for Nuclear Research (Dubna, Russia) [9] as these facilities are commissioned.

An experiment with the Multi-Purpose Detector (MPD) is expected to begin at NICA next year to study nuclear matter produced in collisions of relativistic heavy ions at low temperatures and high net-baryon densities [9]. The MPD experiment will operate both in colliding-beam mode and in fixed-target mode.

The properties of the matter formed in collisions of relativistic heavy ions are determined indirectly by identifying particles produced in such collisions in the experimental setup and measuring their properties by various detector systems. For example, the features of the hadronic phase are measured by identifying the short-lived hadronic resonances [1, 2, 10]. Systematic study of the production of particles with different quark composition, baryon number, mass, strangeness, etc., makes it possible to identify and characterize the processes occurring in hot and dense nuclear matter [1, 11]. Such charged light hadrons as pions, kaons, protons, and antiprotons are of particular interest [11]. These particles are produced in abundance in collisions of heavy relativistic ions. These particles can be easily identified, for example, by their tracks in the magnetic field, energy losses in gas detectors, the square mass or velocity measured by time-of-flight and tracking systems, and/or energy release in the hadron calorimeter.

Charged pions and kaons are called mesons, protons/antiprotons are called baryons. Charged pions consist of the two lightest quarks ($u\bar{d}$, $d\bar{u}$), and measuring their properties is basic for comparison with other particles. Charged kaons ($u\bar{s}$, $s\bar{u}$) possess strangeness, and their mass is almost four times that of pions. Protons (uud) consist of three light quarks, and their mass is almost twice that of kaons [12].

Systematic experimental study of charged hadron production, including their invariant p_T and m_T spectra, integrated yields, and nuclear modification factors, pursues the following goals:

to determine the properties of hot and dense nuclear matter at the time of its decay into final hadrons;

to verify that the system reached thermal and chemical equilibrium;

to evaluate the reaction dynamics, including the collective effects of the longitudinal and transverse fireball expansion.

The reaction dynamics is generally traced by analyzing the shape of the invariant p_T spectra and the mean value $\langle p_T \rangle$ of this momentum.

The shape of these spectra is sensitive to the mechanisms of particle production in various kinematic regions, as well as to the mutual influence of radial flow and parton recombination at intermediate transverse momenta.

Analysis of the shape of invariant transverse mass spectra can be used to determine the kinetic freeze-out temperature and the mean velocity of collective particle flow. Studying the behavior of nuclear modification factors provides an opportunity to assess the severity of collective effects, compared with lighter collision systems at the same collision energy.

To compare the features of particle production, for example, to study the effect of baryon/meson excess yield, a parameter such as their yield ratio is used. Measuring the properties of kaons makes it possible to understand the effect of excess strangeness yield in heavy ion collisions [11].

As in other experiments exploring the properties of hot and dense nuclear matter, measuring the production characteristics of identified charged light hadrons is an integral part of the MPD experiment's physics program. Before the MPD facility is commissioned and starts operation, efforts are underway to develop optimal measurement techniques and estimate their feasibility. Due to the lack of even primary experimental data, such studies are based on model calculations.

The goal of this study was to develop a method for reconstructing the differential transverse momentum spectra of identified light charged hadrons ($\pi^{\pm}$ and $K^{\pm}$ mesons, as well as protons p), using it to assess the feasibility of measuring the properties of these hadrons in collisions of xenon (Xe) nuclei with a fixed tungsten (W) target at incident beam kinetic energy E_{kin} = 2.5 A GeV, where A, u, is the atomic mass number.

It is planned to carry out such measurements at the MPD facility in the central rapidity region, establishing the correlation between these hadron properties and collision centrality.

Experimental setup at the MPD and simulation framework

Characteristics of the experimental setup. This facility was optimized for studying collisions of heavy relativistic ions for high multiplicities of charged particles in the final state. The multiplicity density $dN_{ch}/d\eta$ reaches values of 200–100 at midrapidity for heavy ion collisions at the NICA facility. Here N_{ch} is the number of charged particles in the final state, η is the pseudorapidity.

According to design specifications, the setup is planned to have a wide acceptance and unprecedented resolution in momentum, spatial coordinates, time and energy, especially in the region of low transverse momenta. The tracks and momenta of charged particles will be measured in a Time Projection Chamber (TPC) located in a uniform magnetic field with a strength of 0.5 T generated by a cylindrical solenoid superconducting magnet. The TPC detector will be able to identify charged particles by measuring their energy losses (dE/dx) in the detector's drift gas, consisting of a mixture of argon and methane (90% Ar and 10% CH_4). The particle's charge and momentum will be determined from the curvature of its track in the magnetic field. The TPC will measure up to 53 points along the particle's track. The momentum resolution of the TPC in the region of low transverse momenta in heavy ion collisions will be 1.5–3.5%. The TPC will be able to differentiate hadrons, distinguishing pions from kaons (within two standard deviations) in the momentum range up to 0.7 GeV/c, and kaons from protons in the momentum range up to 1.2 GeV/c. Additional identification of charged particles will be carried out by a Time-Of-Flight (TOF) detector based on the timing measurements. Identification of pions and kaons by the TOF detector will be possible only for particles with p_T above 150 and 350 MeV/c, respectively. Only pions and protons with transverse momenta above these thresholds will be able to reach the TOF detector in the current magnetic field configuration. The latter will provide time-of-flight measurements for charged particles with a typical resolution of about 80 ps. Combined with track reconstruction and measurement of momentum and charge in the TPC, TOF will make it possible to differentiate between charged particles by measuring their velocity β or square mass m^2. In addition, the TOF detector will make it possible to expand the range of transverse momenta where hadrons can be differentiated, namely, to distinguish pions from kaons and kaons from protons with p_T up to 1.5 GeV/c and 2.5 GeV/c, respectively.

Detailed information about the physics program of the future MPD experiment, as well as a description of the detector subsystems included in the experimental setup, are given in [9].

The NICA facility is intended for conducting experiments to collect data from heavy ion collisions both in the configuration with colliding particle beams and with a single beam colliding with a fixed target.

This paper considers a configuration of the accelerator with a fixed target, since it is to be implemented after the MPD detector is commissioned. It is planned to use xenon nuclei as the incident particle beam, while tungsten will serve as the fixed target (made of tungsten wires). The incident beam kinetic energy will amount to E_{kin} = 2.5A GeV, which corresponds to $\sqrt{S_{NN}}$ = 2.87 GeV. The target will be fixed perpendicular to the Z axis at a distance of 85 cm from the geometric center of the MPD towards the incident beam (the Z axis is collinear with the direction of the incident beam).

Simulation framework. In view of the above conditions, collisions of xenon and tungsten (Xe+W) nuclei for the considered configuration were simulated in the UrQMD software package [13], which is the most popular among event generators for the collision energy range implemented at the NICA accelerator. Importantly, the central rapidity region in the center-of-mass system (CMS) is shifted relative to the laboratory frame (by Δy= 0.986) in the experimental setup for Xe+W collisions. This had to be explicitly accounted for in the simulation. We should note that the sample of (Xe+W) collisions in this study was 15 million events.

Full-scale simulation of the responses of detector subsystems to the interaction of particles generated in simulated (Xe+W) collisions with matter of the MPD as well as reconstruction of charged particle tracks were carried out within the MPDRoot software package [9], based on ROOT and Geant4 packages. The MPDRoot software package is written in C++ and serves as the main tool of the MPD experiment both for simulating the operation of detector subsystems and for analyzing data that will be obtained experimentally.

In accordance with the goals of the study, it was especially important to reconstruct the spectra in the central rapidity region in the widest possible range of transverse momenta. Seven centrality bins were selected.

Since the spectra are very soft at such relatively low collision energies ($\sqrt{S_{NN}}$ = 2.87 GeV), i.e., the majority of particles are produced with low transverse momenta, signal reconstruction in the region of low transverse momenta is a crucial challenge. Moreover, asymmetry is observed in the production of positively and negatively charged hadrons in the considered collision configuration. For example, in the case of kaons, the yield of negatively charged particles is significantly suppressed relative to the yield of positively charged kaons, however, no asymmetry is observed for pions. The antiproton yield at the given collision energy is almost zero. In view of the described situation, these calculations were performed separately for positively charged particles and for negatively charged ones.

As noted above, the CMS in the given configuration is displaced relative to the laboratory frame. The central rapidity region in the CMS is of particular interest for our study. However, since this region is close to the boundaries of the geometric acceptance of the TPC, significant non-uniformity was observed in the available phase space (in p_T–y coordinates) for reconstruction of properties of light charged hadrons. Therefore, an asymmetric rapidity range ($-0.5 < y_{\text{CMS}} < 0.0$) was chosen for the analysis; additional constraints for the minimum value of the transverse momentum were imposed for the reconstructed particles.

We propose a new approach to reconstructing the invariant transverse momentum spectra of light charged hadrons ($\pi^{\pm}$, $K^{\pm}$ and p) based on σ-parametrization of particle identification (PID) information in TPC and TOF. This method does not require in-depth systematic study, as it can quickly yield the first physical results immediately after the experimental data are collected.

The proposed method has its own drawbacks and limitations, especially in the region of high transverse momenta, where it can serve as a supplement to other techniques for reconstructing spectra of identified light charged hadrons.

This approach is as follows. At the initial stage of analysis, charged particle tracks are selected from all reconstructed tracks in a given collision. Two criteria were applied to select the tracks: first, a sufficient number of hits must be reconstructed for the track in the TPC; second, the track's distance of closest approach (DCA) to the interaction vertex must be within a specified limit.

The thresholds for these selection criteria are pre-optimized to minimize the number of false reconstructed tracks and to suppress the contribution of secondary particles to the signal (if the losses of signal particles are acceptable).

Four quasi-independent procedures were performed to select hadrons of different types ($\pi^{\pm}$, $K^{\pm}$, and p). The following steps were carried out for protons and charged pions (first two procedures).

First procedure (referred to as '$\pi^{\pm}$, p, TPC + TOF'). The PID cut applied required the candidate particle's signal in the TPC to be within two standard deviations (2σ) of the expected value for the hadron species analyzed. If a track reconstructed in the TPC was matched with a hit in the TOF, an additional 2σ cut (similar to the previous one) was applied for the particle species analyzed, but using the information extracted from the TOF.

Second procedure (referred to as '$\pi^{\pm}$, p, TOF + TPC'). The PID cut applied required the candidate particle's signal to be within 2σ of the expected value for the hadron species analyzed simultaneously in the TPC and TOF.

Two more procedures were used to select another type of hadron, charged kaons: '$K^{\pm}$, TPC + TOF' and '$K^{\pm}$, TOF + TPC'.

Third procedure ('$K^{\pm}$, TPC + TOF'). The PID cut applied required the candidate particle's signal in the TPC to be within one (rather than two) standard deviation of the expected value for the hadron species analyzed. An additional 3σ veto cut was applied to reject background particles identified as protons, pions, electrons, or muons. This cut required that the probability of identifying a candidate as a proton, pion, electron, or muon (based on TPC information) fall outside three standard deviations from the expected value for each of these vetoed particle species.

Fourth procedure (‘$K^{\pm}$, TOF + TPC’). It is similar to the ‘$K^{\pm}$, TPC + TOF’ procedure, but the veto cut was applied to the signal received from the TOF rather than from the TPC.

The described procedures were performed separately for positively and negatively charged particles.

Fig. 1 shows the results obtained on the reconstruction efficiency ε for the spectra of identified charged hadrons using the developed method, for the most central collisions of xenon nuclei with the tungsten target (Xe+W). The reconstruction efficiency function $\varepsilon(p_T)$ depending on the transverse momentum was calculated as the ratio of the number of selected charged species to their total number generated in the event generator.

Analyzing the data in Fig. 1, we can conclude that the spectra of charged kaons are reconstructed less efficiently than the spectra of pions and protons. A significant contamination from pions as well as from electrons and their antiparticles leads to a lower reconstruction efficiency for the charged kaon spectra, especially in the region of low transverse momenta. The decrease in the reconstruction efficiency for the spectra of identified light charged hadrons in the region of low transverse momenta is due to the acceptance of the TPC and higher requirements for the quality of the tracks reconstructed.

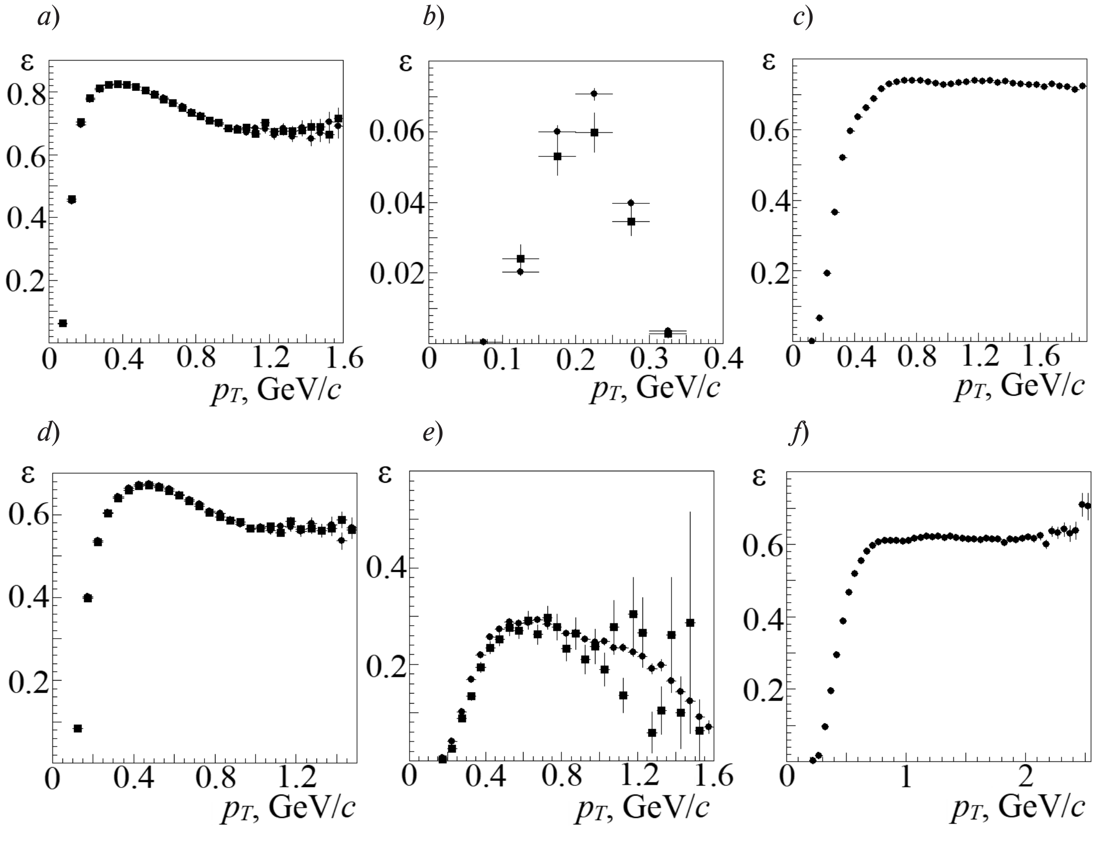

Fig. 1. Computational transverse momentum dependences of reconstruction efficiency for spectra of $\pi^{\pm}$ mesons (*a*, *d*), $K^{\pm}$ (*b*, *e*) mesons and protons (*c*, *f*) using MPD by ($\pi^{\pm}$, *p*, TPC + TOF) (*a*, *c*), ($K^{\pm}$, TPC + TOF) (*b*), ($\pi^{\pm}$, *p*, TOF + TPC) (*d*, *f*) and ($K^{\pm}$, TOF + TPC) (*e*) procedures
The dependences were computed for collisions of Xe nuclei with a W target at $\sqrt{S_{NN}}$ = 2.87 GeV, for negatively (■) and positively (•) charged particles produced

Intermediate spectra of pions, kaons, and protons (dependences of the yield of light hadrons produced in the collisions on the transverse momentum) were obtained from the measurements. Analyzing the spectra, we constructed the dependences of their purity ρ on the transverse momentum. The quantity ρ is the fraction of correctly identified signal particles in the obtained spectrum (PID was carried out based on primary Monte Carlo information about the analyzed tracks).

Fig. 2 shows the dependences of purity ρ on the transverse momentum p_T for the identified light charged hadrons, obtained by applying the constructed procedures for the most central Xe+W collisions. It can be concluded from these data that the proton spectrum does not have any significant contaminations in the entire range of transverse momenta available for analysis. The same picture is observed for the reconstructed spectra of negatively charged pions. As for positively charged pions, their spectrum remains pure up to transverse momenta equal to about 0.8 GeV/*c* and 1.2 GeV/*c*, when the ($\pi^{\pm}$, *p*, TPC + TOF) and ($\pi^{\pm}$, *p*, TOF + TPC) procedures were applied, respectively. The contributions of protons and kaons to the spectrum become significant at higher transverse momenta. Contributions from other particles to the reconstructed spectrum of charged kaons are observed in the regions of both low transverse momenta (electrons, pions) and intermediate and high values (pions).

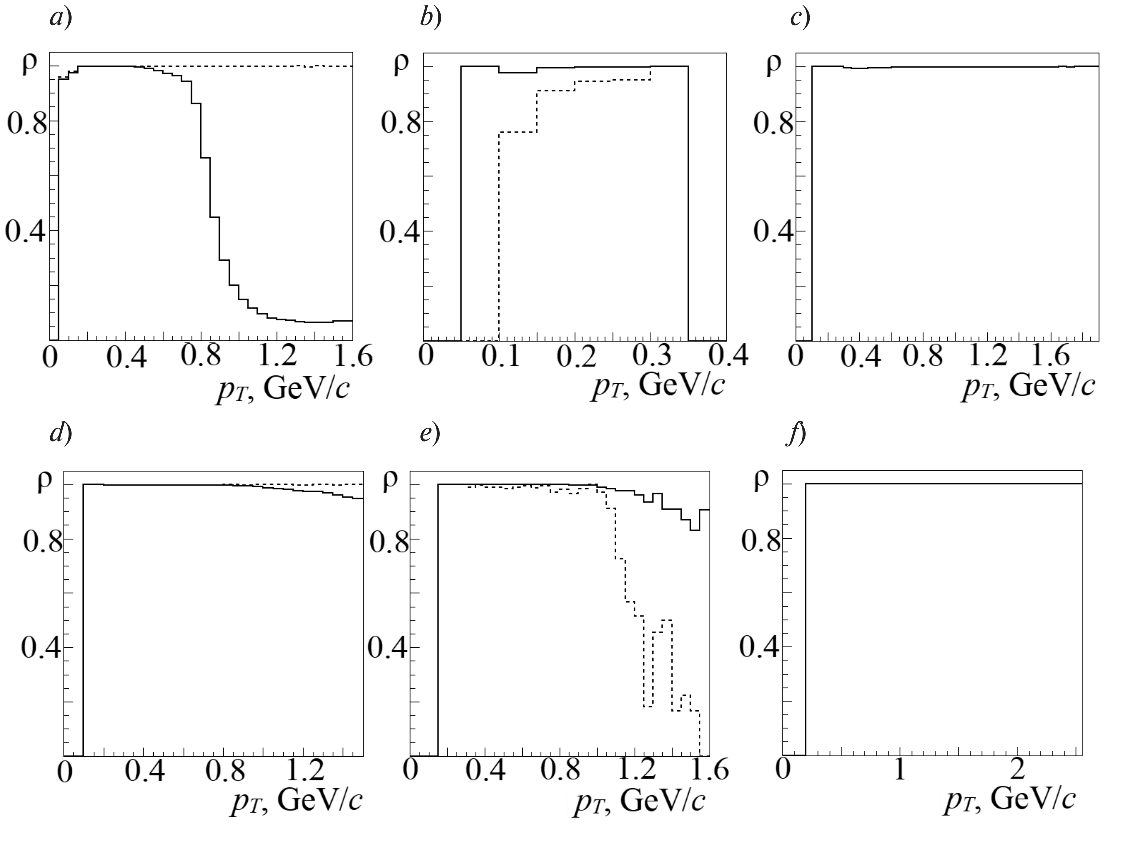

Fig. 2. Computational transverse momentum dependences of purity ρ of reconstructed spectra for $\pi^{\pm}$ mesons (*a*, *d*), $K^{\pm}$ (*b*, *e*) mesons and protons (*c*, *f*), obtained by ($\pi^{\pm}$, *p*, TPC + TOF) (*a*, *c*), ($K^{\pm}$, TPC + TOF) (*b*), ($\pi^{\pm}$, *p*, TOF + TPC) (*d*, *f*) and ($K^{\pm}$, TOF + TPC) (*e*) procedures

The dependences were computed for collisions of Xe nuclei with a W target at $\sqrt{S_{NN}}$ = 2.87 GeV, with negatively (dashed lines) and positively (solid lines) charged particles produced

Spectral purities of at least 95% for pions and protons, at least 90% for kaons, were required to reconstruct the final spectra of the identified light charged hadrons to minimize the systematic uncertainty in the future. This requirement leads to a narrower range of transverse momenta within which the reconstructed spectrum satisfies all conditions of the developed method. An additional constraint had to be imposed on the minimum value of the transverse momentum due to the non-uniform phase space of the reconstructed particle tracks available for analysis.

Once all the described criteria and constraints were satisfied, the raw yield for each identified hadron species was taken as the number of remaining reconstructed tracks. The raw yields were then corrected for reconstruction efficiency and selection purity to obtain the final differential yields. This correction was performed using the following formula [14]:

$$\frac{d^2N}{dp_T dy} = \frac{N(p_T)}{N_{ev}\varepsilon(p_T)\rho(p_T)\Delta p_T \Delta y}, \tag{1}$$

where y is the rapidity of $\pi^{\pm}$, $K^{\pm}$ mesons or protons; p_T, GeV/c, is their transverse momentum; Δp_T, GeV/c, Δy are the transverse momentum and rapidity ranges, within which the particle yield $N(p_T)$ is determined; $\varepsilon(p_T)$ is the reconstruction efficiency of transverse momentum spectra; $\rho(p_T)$ is the purity of the reconstructed spectra; N_{ev} is the number of Xe + W collisions analyzed.

Consequently, the two reconstructed spectra obtained as a result of quasi-independent procedures were combined into a final differential spectrum (depending on the transverse momenta). A spectrum with lower relative statistical uncertainties was selected in the overlap region of the two spectra.

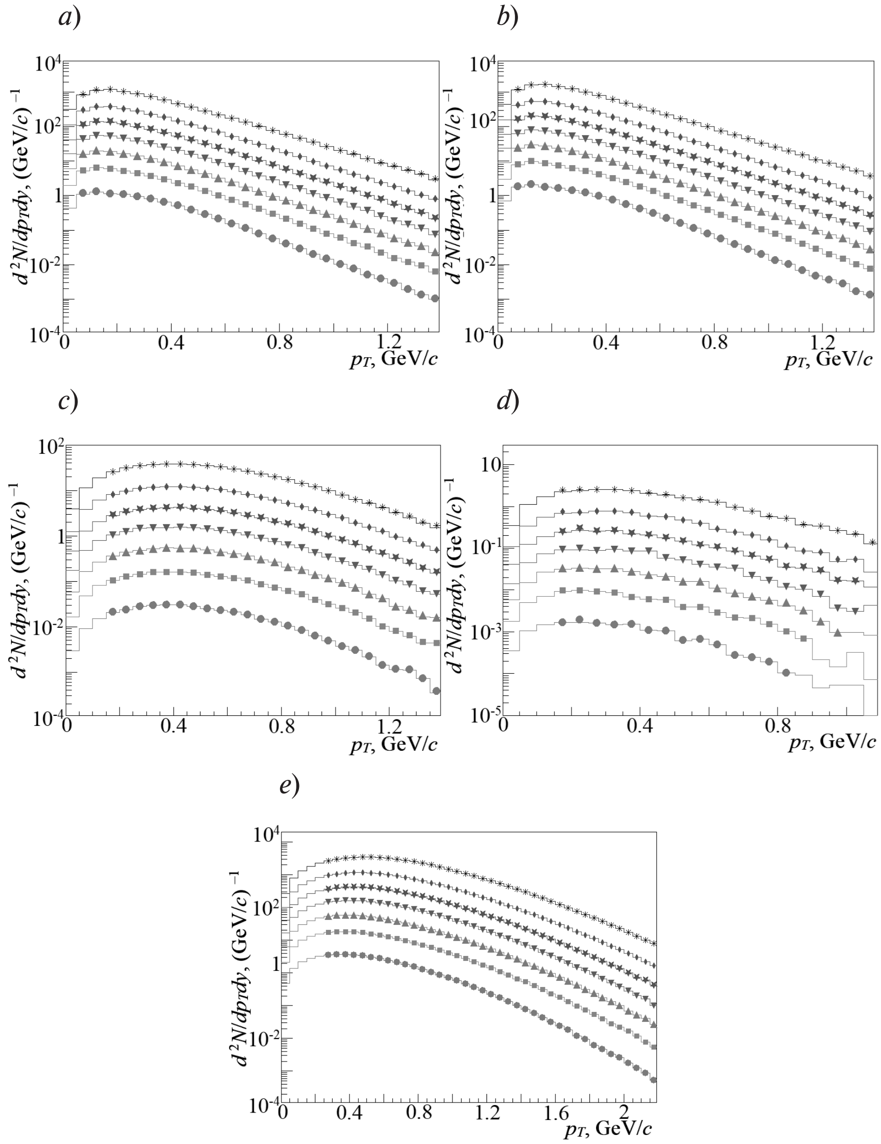

Fig. 3. Reconstructed transverse momentum spectra (symbols) and similar spectra initially modeled by the event generator (lines) for π^+ (*a*), π^- (*b*), K^+ (*c*), K^- (*d*) mesons and protons p (*e*) in the rapidity range -0.5 < y_{CMS} < 0

The spectra were reconstructed for collisions of Xe+W nuclei at $\sqrt{S_{NN}}$ = 2.87 GeV and 7 centrality bins, %: 0–10 (∗), 10–20 (♦), 20–30 (⋆), 30–40 (▼), 40–50 (▲), 50–60 (■) and 60–90(•).
For clarity, the enlarged spectra are shown in one graph

Simulation of reconstructed spectra

Fig. 3 shows the differential spectra of charged pions, kaons, and protons obtained in virtual Xe+W collisions at $\sqrt{S_{NN}}$ = 2.87 GeV in different centrality bins; these spectra were reconstructed using a specially developed method described above. For comparison, the figure also shows the real transverse momentum spectra for the studied hadrons, simulated by an event generator. The spectra appear to be similar, serving to validate the analysis methodology developed in the study.

This method can be used to measure the spectra of the light hadrons under consideration:

charged pions $\pi^{\pm}$ in the central rapidity region at $p_T > 0.05$ GeV/c, which corresponds to approximately 96% of the integrated yield of positively (negatively) charged pions;

charged kaons $K^{\pm}$ at $p_T > 0.15$ GeV/c, which corresponds to about 93% (89%) of the integrated yield of positively (negatively) charged kaons;

protons p at $p_T > 0.25$ GeV/c, which corresponds to about 89% of the integrated proton yield.

The presented method is simple, requiring a minimal number of model-dependent corrections which would need systematic study. Additionally, it enables rapid analysis if experimental data become available.

The presented results confirm that the developed method can be used to reconstruct the spectra in the transverse momentum range necessary for analyzing integrated yields, mean transverse momenta, fitting the spectra by various functions to determine the kinetic freeze-out temperature and the velocity of average collective flow, and extracting other thermodynamic parameters.

Conclusion

The paper explored the feasibility of measuring the properties of $\pi^{\pm}$, $K^{\pm}$ mesons and protons in collisions of xenon nuclei with a fixed tungsten target at incident beam kinetic energy $E_{kin} = 2.5$ A GeV using an experimental setup at the NICA accelerator.

Model calculations were used to obtain estimates of the main process parameters depending on the transverse momentum, such as the purity of the reconstructed spectrum in the MPD setup, the spectrum reconstruction efficiency in this setup, and the transverse momentum spectra for $\pi^{\pm}$, $K^{\pm}$ mesons and protons.

We established that it is sufficient to accumulate more than 15 million collisions to identify and reconstruct the properties of charged hadrons with satisfactory accuracy for studying the production of $\pi^{\pm}$-, $K^{\pm}$ mesons and protons in a wide range of transverse momenta in the central rapidity region using 10% centrality bins for central and semi-central collisions, and 30% bins for peripheral ones

The method for reconstructing the spectra of identified charged hadrons outlined in the paper is fairly simple, requiring a minimum number of model-dependent corrections. It was confirmed that the method can be used to reconstruct the spectra suitable for obtaining integrated yields, mean transverse momenta, and thermodynamic parameters based on them.

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